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(U) EPRI's Non-Contact, Portable Polyphase Current Sensor

Oct. 2012

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ABSTRACT

EPRI has been testing and evaluating a pre-prototype, non-contact, portable sensor that can remotely measure line currents flowing in a polyphase transmission line by means of measuring the external magnetic fields emanating from the line. The geometry of the power line is assumed to be known to an accuracy that can be readily determined from mechanical drawings with the exception that the vertical height of the power lines to ground will be considered to be an unknown. Presently, the system is designed to monitor only the 60 Hz component of line current. However, other harmonics of the fundamental power system and signals propagating on the power system could be readily obtained as well. The constraints on the final sensor system are that it must be field portable, setup time must be short (< 30 minutes) with minimal setup tool utilization, accuracy should be better than 5%, and actual currents flowing through a transmission line cannot be used to calibrate the proposed sensor.

To quantitatively evaluate the feasibility of the concept, the sensor was placed under a 230 kV transmission line that was instrumented at the nearby substation to measure 60 Hz current flowing through each phase. Our paper will describe in detail the sensor, the test setup, and the final results.

1.0 Objectives

Present day measurement techniques utilize clamp-on transformers to determine the flow of current in a power line. This approach while effective has a number of drawbacks associated with working on a live power line because it requires physical contact with a high-voltage line resulting in the need for personal protective equipment and a means to physically reach the line to make the connection.

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE OCT 2012		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE EPRI's Non-Contact, Portable Polyphase Current Sensor				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Electric Power Research Institute (EPRI) Knoxville, TN				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM202976. 2012 Joint Meeting of the Military Sensing Symposia (MSS) held in Washington, DC on October 22-25, 2012.					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

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EPRI has been testing and evaluating a pre-prototype, non-contact, portable sensor that can remotely measure line currents flowing in a multi-phase transmission line by means of measuring the external magnetic fields emanating from the line. The geometry of the power line is assumed to be known to an accuracy that can be readily determined from mechanical drawings with the exception that the vertical height of the power lines to ground will be considered to be an unknown. Presently, the system is designed to monitor only the 60 Hz component of line current. However, other harmonics of the fundamental power system and signals propagating on the power system could be readily obtained as well.

The constraints on the final sensor system are:

1. Field portable,
2. Setup time must be short (< 30 minutes) with minimal setup tool utilization,
3. Accuracy should be better than 5%, and
4. Actual currents flowing through a transmission line cannot be used to calibrate the proposed sensor.

To test for feasibility, a pre-prototype sensor was constructed at EPRI with an equivalent DoD's technology readiness level of 5/6. For this pre-prototype sensor system, the overall accuracy target was increased to 10%. For the rest of this report, reference to the sensor refers to the pre-prototype version.

To quantitatively evaluate the feasibility of the concept, the sensor was placed under a 230 kV transmission line that was instrumented at the nearby substation to measure 60 Hz current flowing through each phase. This report describes the sensor, the test setup, and the final results.

2. Sensor Description

The general layout of the non-contact, current sensor (NCCS) is shown in Fig. 1. There are three pairs of magnetic field sensor heads. Each pair of sensors are arranged in an orthogonal orientation to sense the vertical and horizontal component of magnetic flux. Figure 2 shows an individual pair of sensing heads. Each coil is based on a split design where two coils of equal turns are wound in opposite directions to reduce the effect of the electric field. The shield of the connecting cable is soldered to the midpoint of the coil. Furthermore, the cable wires are a twisted pair to further reduce the effect of both the electric and magnetic fields. Both the horizontal and vertical magnetic sensing coils are identical with each using a 36 gauge wire with 5,000 total turns for each coil. The reason that a 36 gauge wire was selected was to keep the thermal noise to signal ratio small since the magnitude of flux density is a fraction of a μT (as a reference, the earth's magnetic field is around 25 to 65 μT —i.e., we are operating approximately 2 orders-of-magnitude lower than the earth's magnetic field). Both coils in Fig. 2 are mounted on a precision polycarbonate block for a relative accurate orientation of $<1^\circ$.

While the number of turns for each magnetic coil sensor was accurately known along with tight machining tolerances for the coil bobbin (± 0.01 inch machining tolerance on a polycarbonate material), laying the wire on the bobbin is more difficult to control. Based on rough coil calibration measurements, it was estimated that a maximum coil sensing tolerance could vary as much as 10%. In the future, each magnetic coil sensor will be calibrated in a uniform magnetic field, such as a Helmholtz coil, to an accuracy of less than 1%.

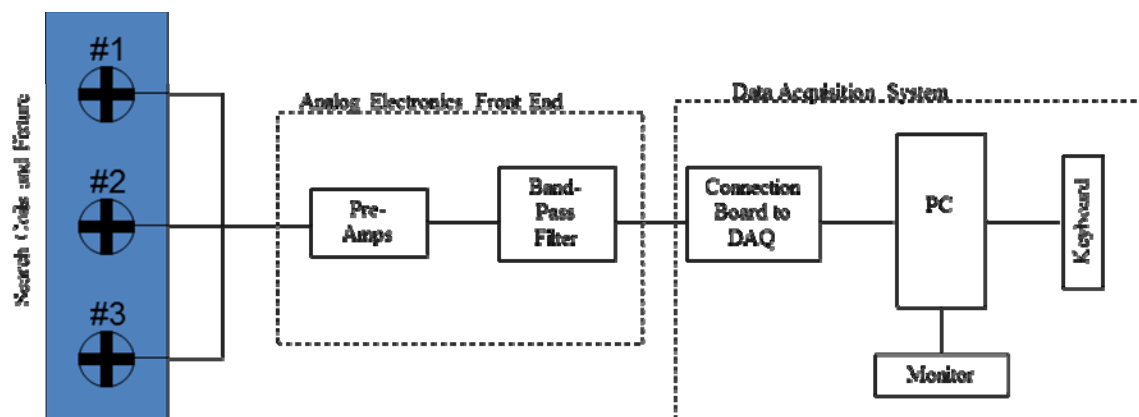


Figure 1. General Layout of Components and Topology



Figure 2. Sensor Head Pair (Note: support block width is 1 inch)

3. Test Case

The 230 kV transmission line that was used for this test was operated by the Southern Company close to Birmingham, Alabama and is shown in Fig. 3. Figure 4 shows the general layout of the sensors on the ground under a 69 kV transmission line. (Note: The pictures of the sensors under the 230 kV transmission line were not included because of the poor picture quality.)



Figure 3. 230 kV Transmission Line



Figure 4a. One Orthogonal Sensor Pair (white screws are orientation screws to be used in conjunction with the green sight vials)



Figure 4b. Three Sensor Pairs and Data Acquisition System Under 69 kV Transmission Line

Due to how the 230 kV line was loaded and the time of year the test was conducted, the line currents were fairly constant during the test. NCCS measurements at the substation were recorded within a few minutes of the manually polled current data from a substation monitor. Because the line currents were consistent throughout the test, only a single reading will be shown. While a statistical inference of the sensor performance cannot be made based on a single set of field test measurements, the performance results of this test at a 230 kV line coupled with results at a 69 kV line do provide a very positive outlook for the feasibility of the concept.

During the 230 kV line test, the individual line currents were measured and are listed in Table 1. Included is the positive-sequence current magnitude which is probably the most significant number since power companies try to minimize all negative- and zero-sequence current contributions.

Table 1. Measured Line Currents at Substation

Measured Currents	Amperes (RMS)
\tilde{I}_a	$506.208 \angle 59.60^\circ$
\tilde{I}_b	$504.390 \angle -60.81^\circ$
\tilde{I}_c	$503.239 \angle -179.15^\circ$
I_+ pos. sequence current	504.574

The vertical height of the transmission line to ground was estimated by a portable laser rangefinder to be $18.4 \text{ m} \pm 0.6 \text{ m}$. While this measurement was not used by the sensor, it was used to obtain a rough error bound generated by the sensor algorithm.

4. NCCS Test Setup

The NCCS was placed underneath the transmission line. The placement of the three sensor pairs was similar to that shown in Figs. 4a and 4b and are arranged so that

1. The reference origin for sensor pair called #3 is placed under the far right line.
2. The reference origin for sensor pair called #1 is placed under the far left line.
3. The reference origin for sensor pair called #2 is placed in the middle of sensor pair #1 and #3.

The sensor pairs are located under the individual transmission line by visual observation. The exact location isn't important; the horizontal offset will be generated by the sensor algorithm to correct for any offset error. Obviously, what is right and left depends on the arbitrary orientation and choice by the human user/observer of the sensor. As long as the sensor pairs #1 and #3 are placed on the outer lines and sensor pair #2 is placed in the middle, the sensor algorithm will work.

Next, each sensor pair is leveled with respect to gravity by means of mechanical adjustment screws located at the base of each sensor pair (see Fig. 4a). This will give the roll and pitch orientation. Orientation along the transmission line (i.e., yaw direction) is done by means of a portable magnetic coil, not shown, that is adjusted by the human operator to obtain this last orientation alignment. The distance between each sensor pair is measured by means of a tape measure and a laser leveler is used to obtain a rough vertical offset between each sensor pair. Accuracies in the Cartesian directions of less than six inches and orientation accuracies of less than 5 degrees are easily doable by a human being in the field and appear to be more than adequate to achieve the line current accuracy targets as will be shown.

Total setup time can be accomplished in under 30 minutes with training. It is envisioned that this number could be significantly reduced for a deployable sensor package.

5. NCCS Results

5.1 Objective

The NCCS must determine each phase current and all unknown geometric parameters such as vertical height and horizontal offset. Measured phase currents and a rough estimate of the vertical height will be used to judge the feasibility of the proposed sensor concept. The horizontal offset cannot be measured in the current set up procedure.

5.2 Vertical Estimate

A laser rangefinder was used to take a rough estimate of the transmission line height. The value recorded by this device was approximately $18.4 \text{ m} \pm 0.6 \text{ m}$ with respect to ground. The algorithm used by the NCCS is based on minimizing the error of the voltage measured at each coil based on an ideal transmission line model. The estimate for the vertical height is where the least-square error term is minimized. Figure 5 shows the error plot as a function of vertical height. The vertical axis units are in units of voltage and the horizontal axis is the vertical height in units of meters. The algorithm estimated the vertical height as 18.1 m. This was an error of 2 to 5%, which provides credibility to the results.

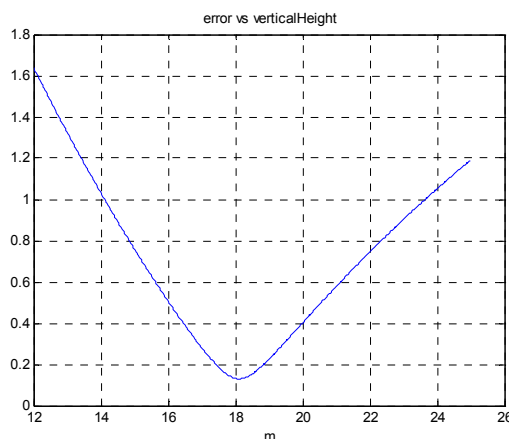


Figure 5. Error Criteria versus Vertical Height

5.2 Current Estimate

The estimated current magnitudes are shown in Fig. 6. The values are compared to the measured values from the substation in Table 1. The individual phase currents varied from 2% to 6% error as shown in Table 2. The sequence currents are compared to the measured values in Table 3. Note that for both Tables 2 and 3, only three significant digits are shown for the measured (substation) and estimated (NCCS) values. The positive-sequence current error was 1%.

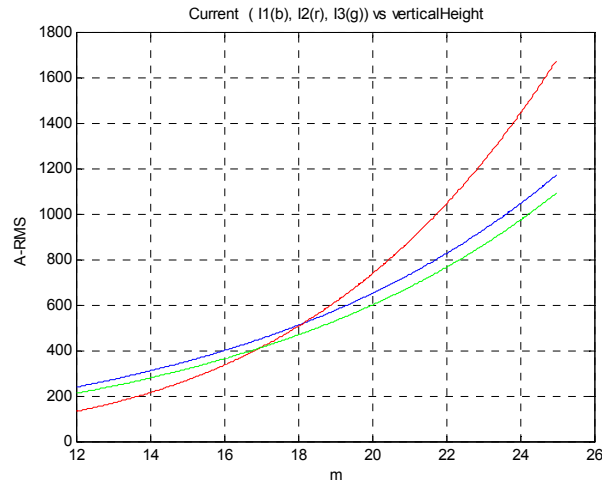
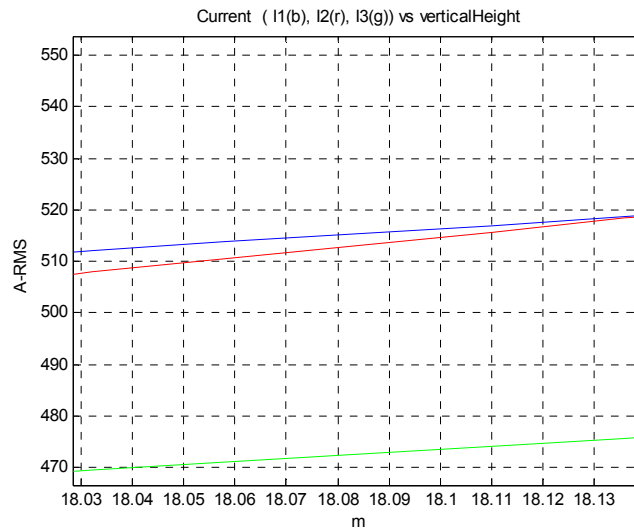


Figure 6a. Estimated Phase Currents as a Function of Vertical Height



**Figure 6b. Estimated Phase Currents as a Function of Vertical Height
(Zoomed version of Figure 6a)**

Table 2. Phase Current Errors

Phase Currents	Measured at Substation	Estimated by NCCS	Error (%)
I_a	506	516	2%
I_b	504	514	2%
I_c	503	473	6%

Table 3. Positive Sequence Current Errors

Sequence Current	Measured at Substation	Estimated by NCCS	Error (%)
I_+	505	501	1%

As mentioned previously, while a statistical inference of the sensor performance cannot be made based on only one or two field tests, the results do provide significant credibility and feasibility to the overall concept.

5. Summary

The design goal of this project has been a non-contact current sensor that could estimate the phase currents within an accuracy of 10% for the pre-prototype system. Presently, we are at 6% for the pre-prototype system. Additional system design modifications and sensor head calibration should reduce this error even further. The main errors appear to be due to setup calibration errors and in the sensing coil fabrication process. A technology pathway appears to exist to make the system backpack portable. The major technology risk appears to be solved. The next step in the R&D cycle could take two different paths: work with a potential end-user of the technology to create functional and design specifications focused on specific CONOPs or improve the generic design to enhance the ease-of-use (faster setup, reduce positioning error, etc.) and improve measurement accuracy and calibration. Regardless of which path the R&D takes, infrastructure requirements by EPRI appear to be minimal and mainly encompass calibration equipment.